Numerical simulation of shot dynamics and the material surface condition of IN718 after ultrasonic shot peening

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Abstract: Ultrasonic shot peening (USP) is a mechanical surface treatment process used to enhance the fatigue life of high-added value components. During the process the shots are accelerated by a mechanical actor stimulated with a frequency between 15-40 kHz. In contrast to conventional shot peening (CSP) the shot velocities are lower and the mass of the shots are higher. For optimization of the process parameter without large experimental effort it is necessary to describe the condition in the surface layer (residual stress, surface topology) after the process depending on the process parameter. For this it is essential that the stochastic distribution of the shots and their impact velocities are known. During this work a multiple-step numerical simulation was performed to calculate first the distribution and velocity of the shots and use this information in the second step to apply an FE-analysis on a limited area to calculate the surface characteristics. An advanced hardening model was implemented to describe the effect of nonlinear combined isotropic-kinematic hardening and strain rate dependent yield at once. Subsequently, the numerically determined residual stresses were compared with experimental measurements by X-ray and synchrotron diffraction.

Specimen peening

It has been demonstrated that USP strongly increases the fatigue life of mechanical components [1] [2] [3] [4]. The principle of an ultrasonic shot peening system is shown in figure 1. The system is powered by ultrasonic frequency generator generating a frequency of 15 kHz to 40 kHz with a piezo actor. The resulting oscillation is reinforced about a booster and stimulates finally the sonotrode. In that way, the shots in the chamber were accelerated resulting in a high number of impacts in a comparably short time. The investigated material was an IN718 alloy taken from a round bar with a diameter of 35mm and has a corresponding hardness between 240 HV1 and 270 HV1. The chemical composition is shown in Table 1. The material was annealed with at 955°C and subsequently quenched with water. After cutting the specimens were polished with 9 µm diamond solution in order to easily observe the coverage after peening.

Table 1: Chemical composition of IN718

Element	Ni	Fe	Cr	Mn	Mo	Ti	Al	Si	C
wt.%	balanced	18.87	18.28	0.08	2.89	0.98	0.56	0.08	0.04

The surface treatment was performed using steel shots made of 100C6 with an average diameter of 0.984 mm and a hardness of 772 HV1. The grade of the shots were G100 according to ISO3290. The treatment was performed using the USP-device STRESSVOYAGER of the company SONATS. A sonotrode with a diameter of 50 mm and a round chamber with the same diameter were used. The sonotrode was placed at the bottom of the chamber. The distance between sonotrode and specimen was 20 mm. The total ball mass was 2.5 gram and the vibration amplitude was 80 µm. The treatment time was 10 s. The achieved coverage C, defined as the ratio between the surface that was hit by at least one shot to the complete surface in percent, should be around 100%.

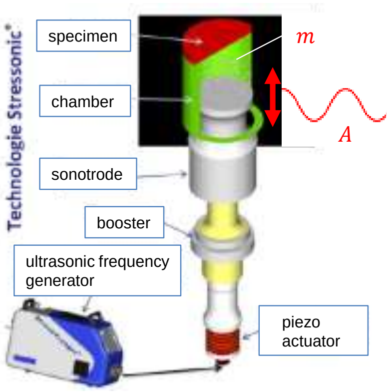

Fig. 1: Principle of ultrasonic shot peening system

The intensity of the treatment was measured with Almen strips according to SAE J442 standard, showing that the peening intensity was F18.9A at 11.6 s. The treated specimens, the sonotrode and the used chamber are shown in Fig. 2.

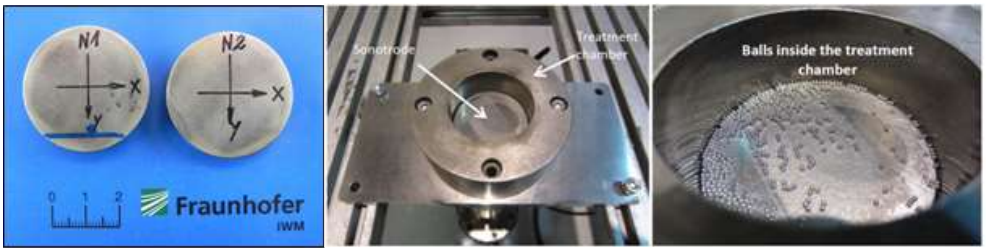

Fig. 2: (a) Treated specimen made of IN718, (b) Prepared sonotrode for USP, (c) Chamber

Material characterization

The hardening behavior of the IN718 alloy at high plastic strains was determined by five compressions test. The specimens had a nominal diameter of 10 mm and a nominal length of 15 mm. For the determination of the back stress (Bauschinger effect) during cyclic loading of the material strain controlled cyclic tension-compression tests at different constant strain amplitudes were used to describe the cyclic stress strain behavior. Further to that cyclic tests with gradually increasing strain amplitude from 2 % to 8 % were performed.

Simulation of the peening process

FE-model

The simulation of the ultrasonic surface treatment was performed with the commercial software package ABAQUS©, version 6.14. The model in this work was a 3D model used to simulate the USP-process on a representative section according to the real specimen. The dimensions of this model are illustrated in Fig. 3. The treated surface had a size of 1 mm^2. 8-node continuum full-integrated elements with hourglass-control (C3D8) were used in this zone to the depth of 0.5 mm. Surrounded by 8-node continuum with induced integration and hourglass-control (C3D8R). All edges except the top surface are covered with infinite 3D-elements (CIN3D8). This modelling technique has been previously used in [5-9].

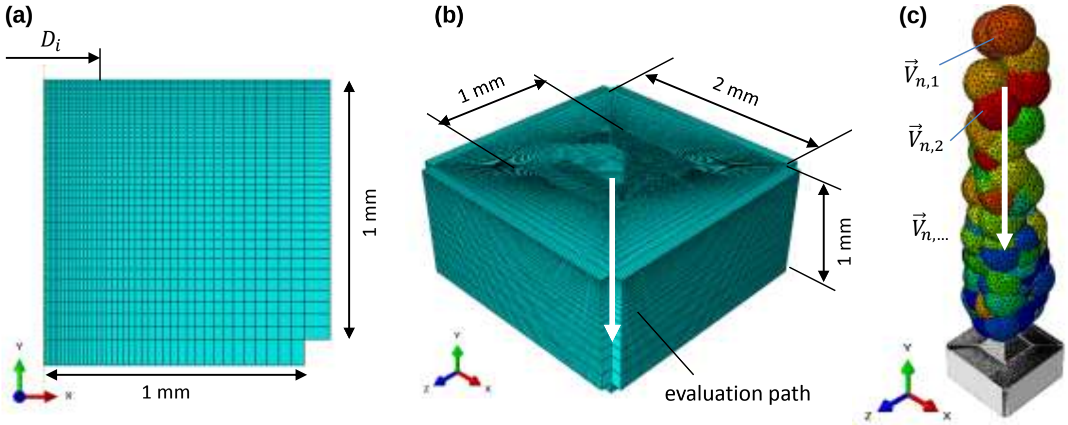

Fig. 3: (a) Axisymmetric 2D model, (b) 3D model with the corresponding dimensions for simulation and (c) complete model for USP simulation with meshed spheres with corresponding impact velocities

Constitutive model

Two different material conditions were investigated in this study:

Condition A: IN718 alloy with a hardness of 249 HV averaged from 10 hardness measurements and a yield stress of 565 MPa. The material was annealed but not age hardened.

Condition B: Age hardened IN718 alloy with a hardness of 550 HV and a 0.2% offset yield stress of 1200 MPa. The mechanical properties are taken from literature [10].

Elastic material behavior of IN718 was expressed with Young's modulus of E=200 GPa and Poisson's ration of v=0.32 for all constitutive models. In this work the effect of isotropic, kinematic and strain rate dependent hardening was investigated separately. The parameters for the constitutive models are summarized in table 2.

Table 2: Parameters for the used constitutive models for the FE-analysis

Parameter / Const. model	A: not age hardened IN718 alloy		B: age hardened IN718 alloy		Units
	[11]	[12]	[11]	[12]	
D_0	$9.755 \cdot 10^9$		10^6		s^{-1}
n	0.215		1.97		-
Z_0	1536930		3095		MPa
Z_1	4341670		1900		MPa
m	4.404		200		-
C_1		181289		12390	MPa
γ_1		419.923		31.53	-
C_2		3620.11		123090	MPa
γ_2		20.2702		219.77	-

Results

Fig. 4 shows the experimental and numerical determined residual stress depth profiles. As illustrated in Fig. (a), the influence of the shot material behavior seems to be relatively high. For rigid shot behavior the maximum transverse stress was -867 MPa, for elastic behavior -785 MPa and for plastic shot behavior -773 MPa. For these investigations the constitutive model of the target material was assumed as nonlinear isotropic. The investigated maximum stress value for kinematic material behavior was -742 MPa and for strain rate-dependent material behavior -1035 MPa. Another calculation for condition B was done with the Ramaswamy constitutive model, see 4 (b), using the determined model parameters. The minimum stress value is -719 MPa. For these investigations the shots are assumed as rigid.

As shown, the stress values measured with synchrotron diffraction at the surface of the specimen out of IN718, had a range from -579 MPa to -787 MPa. The surface stress value measured with X-ray diffraction has a value of -688 MPa. Surprisingly, best agreement of numerical and experimental determined and residual stress values were reached with the Ramaswany-Stouffer constitutive model for material condition B. However, all simulations underestimate the surface residual stress state according to the experimental residual stress measurements.

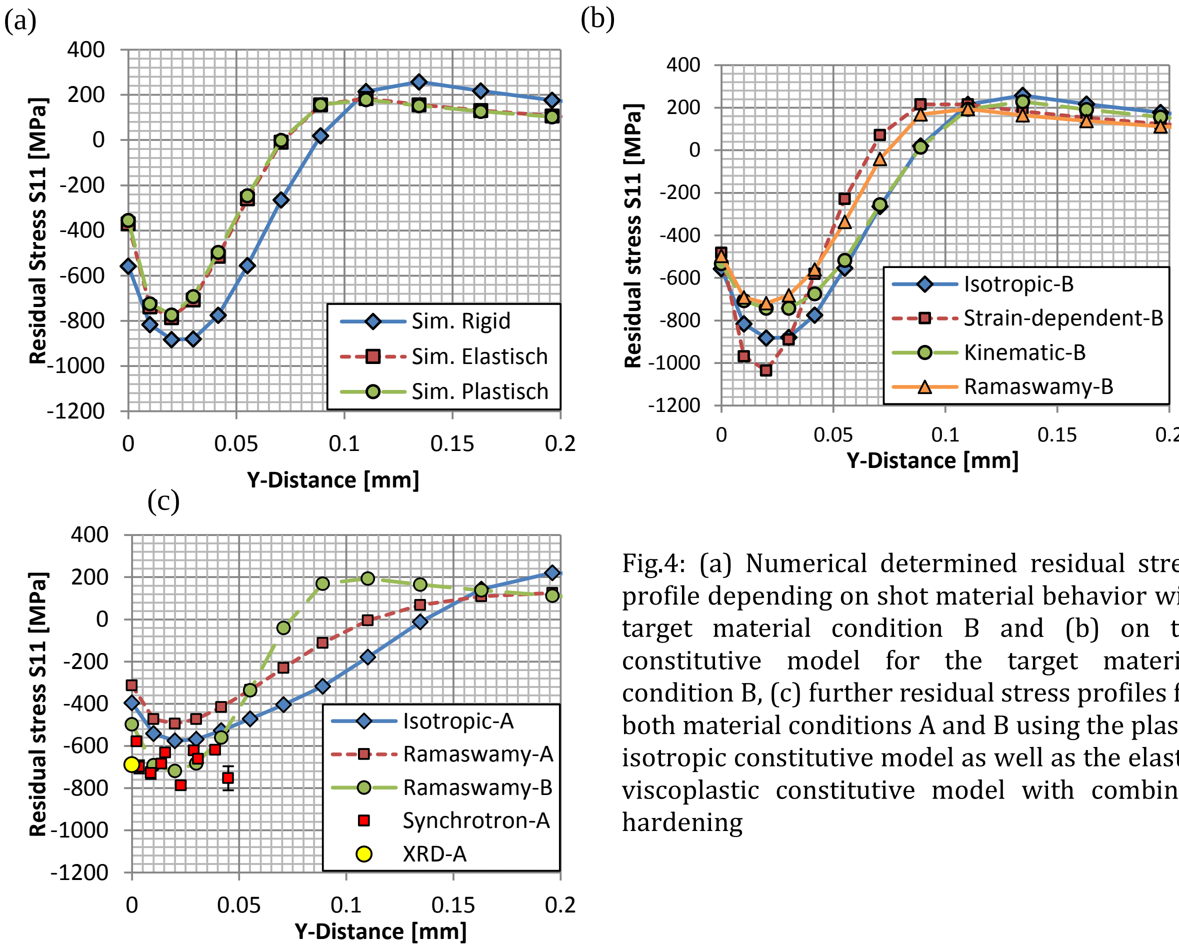

Fig.4: (a) Numerical determined residual stress profile depending on shot material behavior with target material condition B and (b) on the constitutive model for the target material, condition B, (c) further residual stress profiles for both material conditions A and B using the plastic isotropic constitutive model as well as the elasto-viscoplastic constitutive model with combined hardening

Conclusion

It was shown that the material behavior of the shots could have a high influence on the induced residual stress profile. However, as shown the mesh size of shots can also influence the residual stress state of the target. Further investigations with different mesh sizes are needed to quantify these influences. Furthermore, it could be shown that kinematic hardening significantly reduces the residual stress after peening.

Best agreement of numerical and experimental determined stress values could be reached for simulation with rigid sphere and nonlinear kinematic or isotropic hardening calibrated according to material condition A. The influence of the shot material behavior to the surface stress state after peening seems higher than the influence of the constitutive target model in this case.

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